FAST DEFLAGRATION-TO-DETONATION TRANSITION IN HELICAL TUBES

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Abstract: When designing a new type of power plants operating on pulsed detonations of gaseous or liquid fuels, the concept of fast deflagration-to-detonation transition (FDDT) is used. According to the concept, the flame arising from a weak ignition source must accelerate so fast as to form an intense shock wave at a minimum distance from the ignition source so that the intensity of the shock wave is sufficient for fast shock-to-detonation transition due to some additional arrangements. Hence, the FDDT concept implies the use of special means for flame acceleration and shock wave amplification. In the present work, FDDT has been studied using a standard pulsed detonation tube (SDT) comprising a Shchelkin spiral and a helical tube section with ten coils as the means for flame acceleration and shock amplification (focusing) devices, respectively. To attain the FDDT at the shortest distances for fuels of essentially different detonability, the diameter of the SDT is taken close to the limiting diameter of detonation propagation for air mixtures of regular hydrocarbon fuels (50 mm). The experiments have been conducted with air mixtures of individual gaseous fuels (hydrogen, methane, propane, and ethylene) and binary fuel compositions (methane–hydrogen, propane–hydrogen, and ethylene–hydrogen) at normal pressure and temperature conditions. The use of the helical tube with ten coils is shown to considerably extend the fuel-lean concentration limits of detonation as compared to the straight tube and a tube with a helical section with two coils.

Keywords: standard pulsed detonation tube; fast deflagration-to-detonation transition; detonability; hydrogen; methane; propane; ethylene; blended hydrogenous fuels

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Figure Captions

Figure 1 Schematics of SDT-1 (*a*) and SDT-2 (*b*). Dimensions are given in millimeters

Figure 2 Schematic of the experimental setup with SDT-2

Figure 3 D–x diagrams for several shots with a fuel-lean hydrogen–air mixture with $\Phi \approx 0.5$: (*a*) 17.2 %(vol.) H_2 – air mixture, SDT-1; (*b*) 17.3 %(vol.) H_2 – air mixture, SDT-2; horizontal dotted lines correspond to Chapman–Jouguet detonation velocity; different signs correspond to different shots; empty signs connected by a dashed line correspond to reaction front velocity; and filled signs connected by a solid line correspond to shock wave velocity

Figure 4 D–x diagrams for several shots with a fuel-lean 12% (vol.) H_2 – air mixture ($\Phi \approx 0.325$): (*a*) SDT-1; and (*b*) SDT-2. The horizontal dotted lines correspond (from bottom to top) with the velocity of sound in the initial mixture, the velocity of sound in the detonation products, and the Chapman–Jouguet detonation velocity; different signs correspond to different shots; empty signs connected by a dashed correspond to reaction front velocity; and filled signs connected by a solid line correspond to shock wave velocity

Figure 5 Dependences of the propagation velocities of the reaction front and the flame-born shock wave measured in different sections of SDT-2 on the fuel-to-air equivalence ratio Φ in the hydrogen–air mixture: solid curve — Chapman–Jouguet detonation velocity D_{CJ}; filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — velocity at the measuring section of the pipe; *2* — velocity on a spiral section of the pipe; and *3* — velocity at the entrance to the spiral section of the pipe

Figure 6 Comparison of the measured detonation velocities in the last coil of the helical tube section in SDT-1 and SDT-2 on the fuel-to-air equivalence ratio Φ in the hydrogen–air mixture: filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — velocity at the exit from the last turn of the spiral pipe SDT-1; and *2* — steady speed in the section of the spiral pipe SDT-2

Figure 7 D–x diagrams for several shots with the stoichiometric methane–air mixture ($\Phi = 1$): (*a*) SDT-1; and (*b*) SDT-2; horizontal dotted lines correspond to Chapman–Jouguet detonation velocity; different signs correspond to different shots; empty signs connected by a dashed line correspond to reaction front velocity; and filled signs connected by a solid line correspond to shock wave velocity

Figure 8 D–x diagrams for several shots with the fuel-lean methane–hydrogen–air mixtures in SDT-2: (*a*) $1\%\,CH_4 + 10\%\,H_2 + 89\%$ air mixture, $\Phi = 0.38$; (*b*) $1.14\%\,CH_4 + 10.3\%\,H_2 + 88.6\%$ air, $\Phi = 0.40$; horizontal dotted lines correspond to Chapman–Jouguet detonation velocity; different signs correspond to different shots; empty signs connected by a dashed line correspond to reaction front velocity; and filled signs connected by a solid line correspond to shock wave velocity

Figure 9 Dependences of the propagation velocities of the reaction front and the flame-born shock wave measured in different sections of SDT-2 on the fuel-to-air equivalence ratio Φ in the blended ($10\%\,CH_4 + 90\%\,H_2$) fuel–air mixture: solid curve — D_{CJ}; filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — velocity at the measuring section of the pipe; *2* — velocity in the section of the spiral pipe; and *3* — velocity at the inlet of the spiral pipe

Figure 10 Dependences of the propagation velocities of the reaction front and the flame-born shock wave measured in the last coil of the helical tube section in SDT-2 on the fuel-to-air equivalence ratio Φ in methane–hydrogen–air mixtures with different dilution of hydrogen with methane: filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — $100\%\,H_2$; *2* — $10\%\,CH_4 + 90\%\,H_2$; *3* — $20\%\,CH_4 + 80\%\,H_2$; *4* — $40\%\,CH_4 + 60\%\,H_2$; and *5* — modes with detonation in the spiral section and detonation stall in the measuring section (see Appendix)

Figure 11 Records of pressure sensors Nos. 16, 19, and 21 in the measuring section of SDT-2 in three successive shots with ($20\%\,CH_4 + 80\%\,H_2$) – air mixture at $\Phi = 0.54$

Figure 12 Dependences of the propagation velocities of the reaction front and the flame-born shock wave measured in the last coil of the helical tube section in SDT-2 on the fuel-to-air equivalence ratio Φ in propane–hydrogen–air mixtures with different dilution of hydrogen with propane: filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — $100\%\,H_2$; *2* — $10\%\,C_3H_8 + 90\%\,H_2$; *3* — $20\%\,C_3H_8 + 80\%\,H_2$; and *4* — $40\%\,C_3H_8 + 60\%\,H_2$

Figure 13 Dependences of the measured propagation velocities of the reaction front and the flame-born shock wave in the measuring section of SDT-2 on the fuel-to-air equivalence ratio Φ in ethylene–hydrogen–air mixtures with different dilution of hydrogen with ethylene: filled signs — shock wave velocity D_{SW}; empty signs — reaction front velocity D_f; *1* — $100\%\,H_2$; *2* — $10\%\,C_3H_8 + 90\%\,H_2$; *3* — $20\%\,C_3H_8 + 80\%\,H_2$; *4* — $30\%\,C_2H_4 + 70\%\,H_2$; and *5* — $40\%\,C_3H_8 + 60\%\,H_2$

Figure 14 D–x diagrams for several shots with a fuel-lean ($30\%C_2H_4 + 70\%\,H_2$) – air mixture with $\Phi = 0.50$: (*a*) SDT-1, no detonation; (*b*) SDT-2, detonation in the helical tube section and in the measuring section; horizontal dotted lines correspond to Chapman–Jouguet detonation velocity; different signs correspond to different shots; empty signs connected by a dashed line correspond to reaction front velocity; and filled signs connected by a solid line correspond to shock wave velocity

Table Caption

Table 1 Schemes of installation of ionization probes and pressure sensors in SDT-1 and SDT-2

Table 2 Natural gas composition (%(vol.))

Appendix Summary table of experiments conducted in SDT-2 facility with air mixtures of unitary and binary fuels

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